Towards a Predictive Capability for Laser Backscatter in NIF Ignition Targets

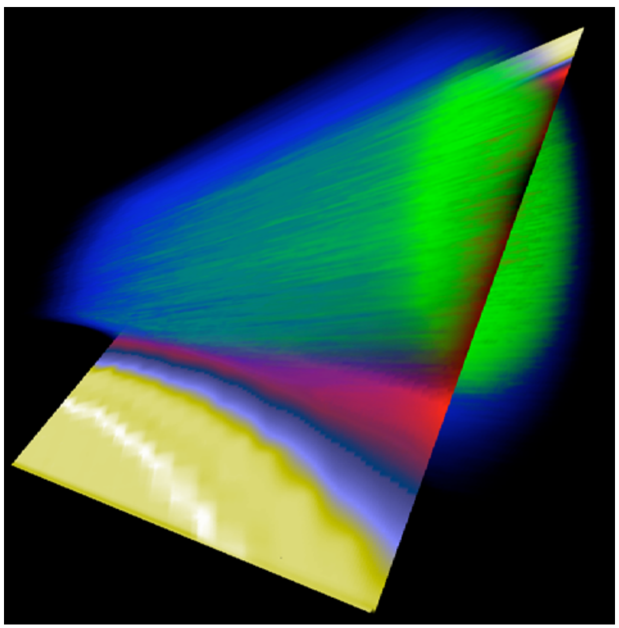
Presented to:

2nd Annual Computing Grand Challenge Symposium

Lawrence Livermore National Laboratory

Livermore, CA, USA

February 20, 2008



D. E. Hinkel, C. H. Still,

A. B. Langdon, S. H. Langer,

and E. A. Williams

LLNL-PRES-401555

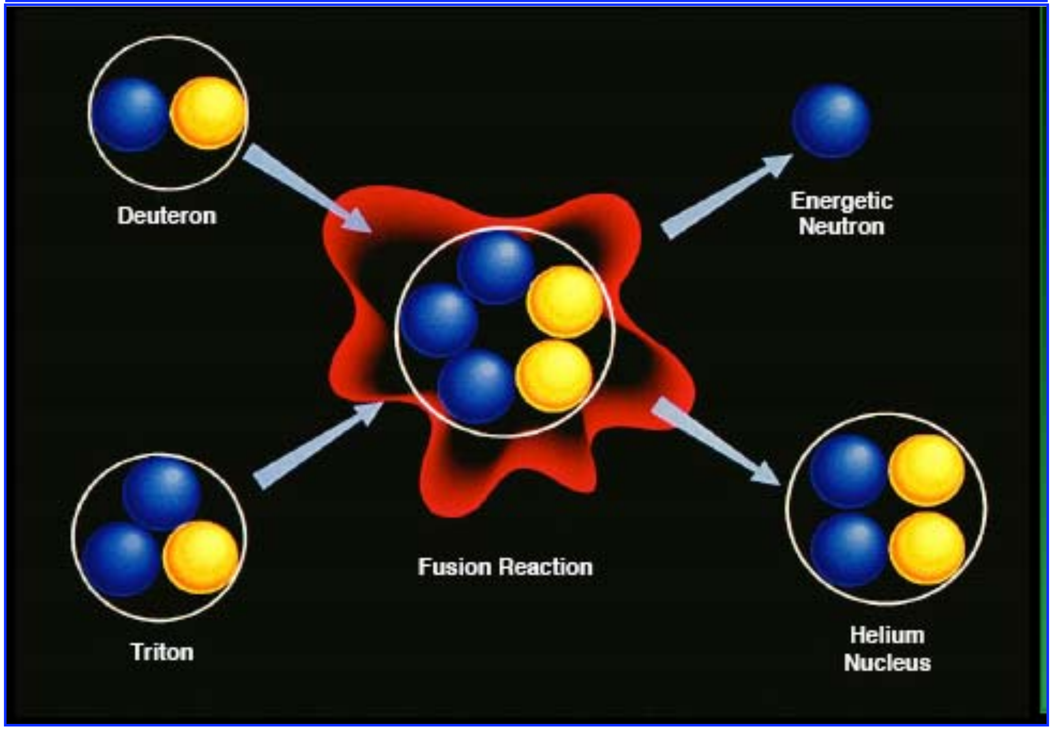
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551-0808

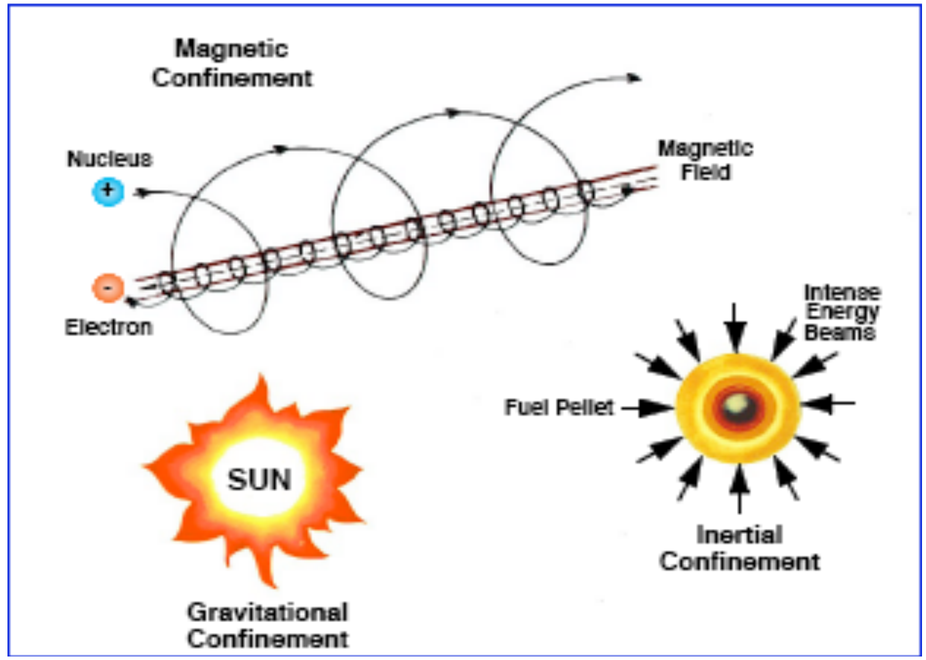
Fusion powers the sun and the stars … and maybe one day our communities

The National Ignition Campaign

Fusing deuterium and tritium into a helium nucleus releases an energetic neutron



Fusion is accomplished via gravitational, magnetic and inertial confinement

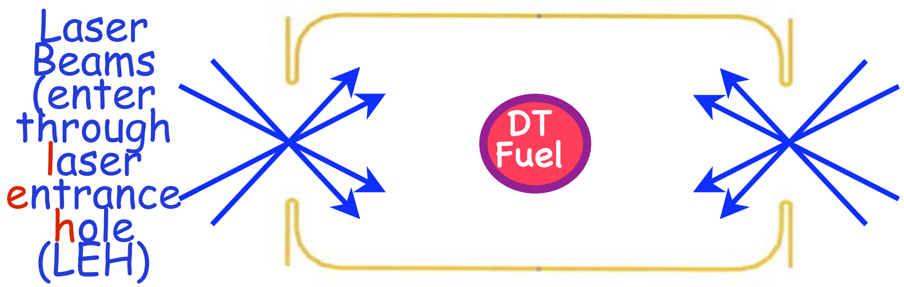


The goal of upcoming experiments on the National Ignition Facility (NIF) is to achieve fusion in a laboratory setting

Inertial confinement fusion (ICF) relies on the inertia of the fuel to provide confinement

The National Ignition Campaign

- <u>INDIRECT DRIVE:</u> laser energy is converted to x-ray energy by target



Hohlraum (laser target)

- x-rays bathe ICF capsule, heating it up -- it expands

Ablator heats up

- conservation of momentum: ablated shell expands outward, rest of shell (frozen DT) is forced inward

Rocket effect

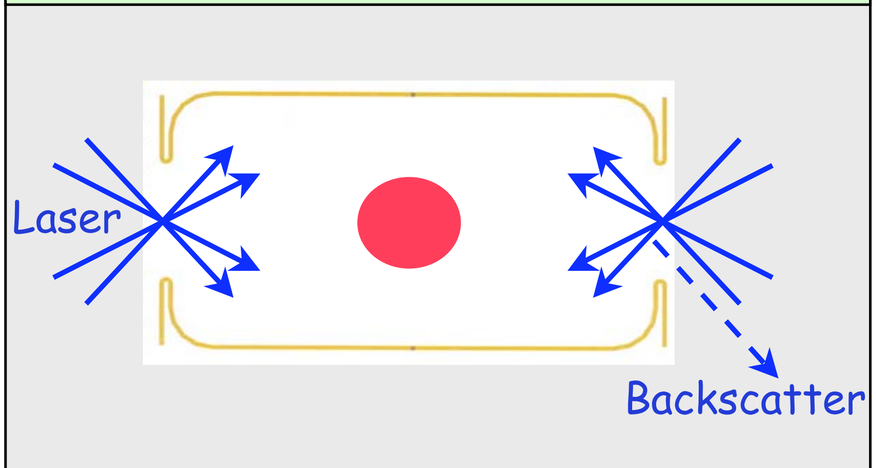
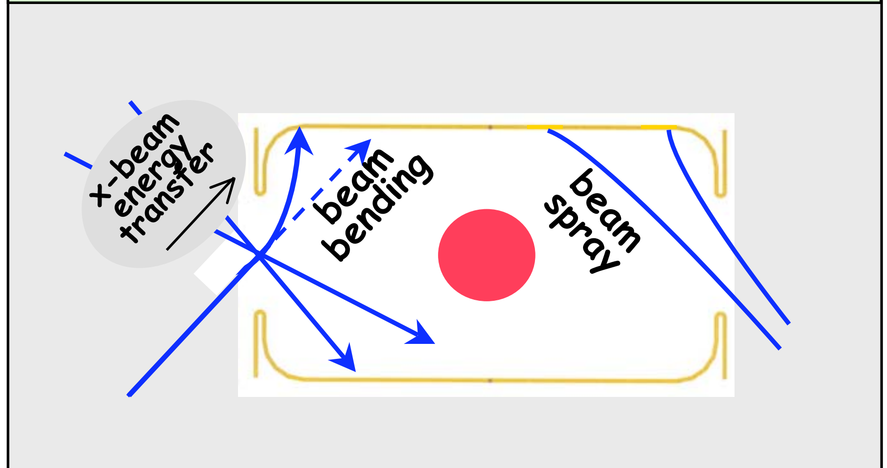
- fusion initiates in a central hot spot containing ~ 5% of the fuel, and a thermo-nuclear burn front propagates outward

Ignition

Burn wave

Laser-plasma interactions (LPI) can result in direct energy loss or re-direction for laser-driven targets

The National Ignition Campaign

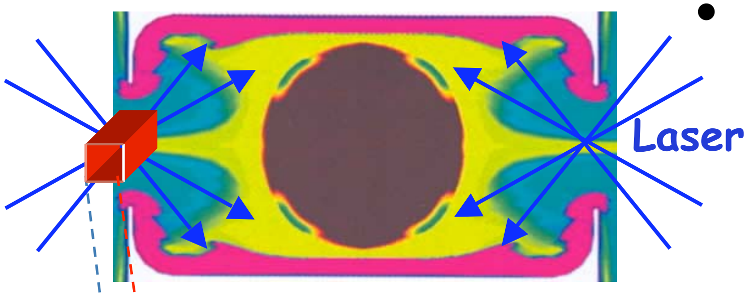
Energy Loss $\Rightarrow$ low T_r	Energy Re-direction $\Rightarrow$ symmetry loss
	
<u>SBS</u>: laser scatters off self-generated ion acoustic waves (iaws) <u>SRS</u>: laser scatters off self-generated electron plasma waves (epws)	Beam spray: laser hotspots dig density wells -- refract, intensify & scatter light Beam bending: in transverse flow, light advects with density wells Crossed beam transfer: inner-to-outer energy transfer via scatter from mutually driven iaws

Our focus is on LPI mitigation in NIF ignition targets

LPI processes span a wide range of length and time scales

The National Ignition Campaign

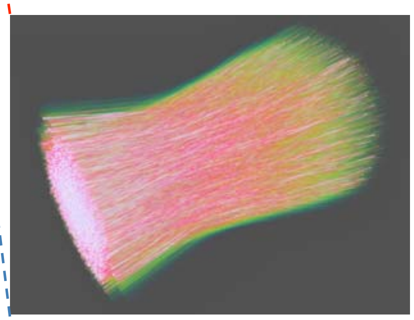
macroscale



- **Hydrodynamic length and time scales are set by target size [O(mm)] and laser pulse length [O(ns)]**

  ⇒ environment -- plasma parameters and scale lengths

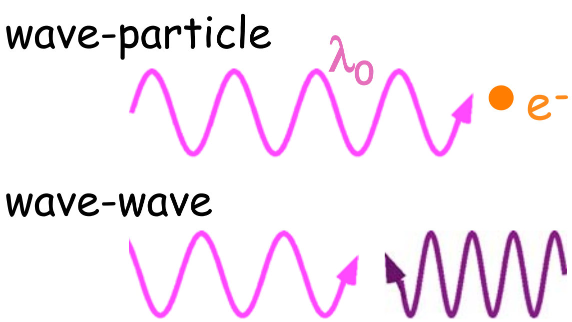
mesoscale



- **LPI evolves on: μm length scales and ps time scales**

  ⇒ beam propagation

microscale



- **Detailed processes of LPI occur on "light" spatial and temporal scales**

  ⇒ kinetic effects

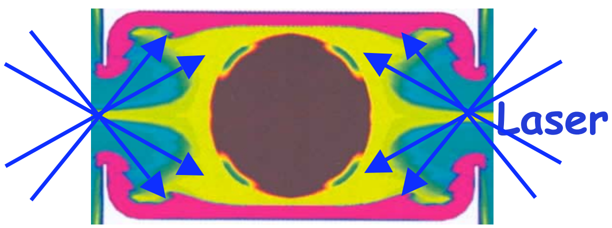
Our challenge: incorporate all necessary physics at all relevant length and time scales

Our approach to multi-scale modeling uses a suite of tools

The National Ignition Campaign

macroscale

Lasnex/Hydra

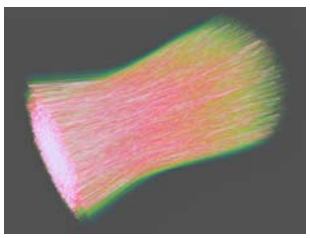


Radiation/Hydrodynamics simulations

laser energy → heat e^{-}'s → make x-rays; hydro motion → implosion & burn

mesoscale

pF3D

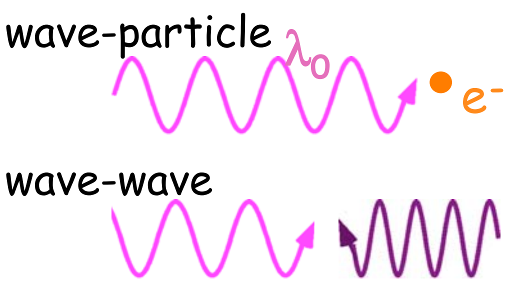


Wave propagation simulations

incident laser propagation (paraxial) ↔ fluid plasma model ↔ scattered light propagation (paraxial)

microscale

Z3/BZohar



Particle in cell (PIC) simulations

particle phase space → Maxwell Equations (ρ,**j**) → EM fields

EM fields → Lorentz Force → particle phase space

Multi-scale codes, beam data & validation ⇒ development of a predictive capability

pFF3D simulations couple wave propagation (paraxial) to a plasma fluid model

- paraxial wave equation spatially/temporally envelopes about local wavenumber/frequency:

$$\left(\underbrace{\frac{\partial}{\partial t}+\upsilon_g\frac{\partial}{\partial z}}_{\text{advection}}-\underbrace{\frac{ic^2}{2\omega_0}\nabla_\perp^2}_{\text{propagation}}+\frac{1}{2}\frac{d\upsilon_g}{dz}+\underbrace{\nu}_{\text{absorption}}\right)E_0=\frac{i\omega_{pe}^2}{2\omega_0}\frac{1}{n_e}\left(\underbrace{\boxed{\delta n_e E_0}}_{\text{refraction}}+\underbrace{\boxed{\delta n_b E_b}}_{\text{SBS coupling}}+\underbrace{\boxed{\delta n_r E_r}}_{\text{SRS coupling}}\right)$$

Fields

E_0 : incident laser

E_b : SBS; driven by $\delta n_b E_0$

E_r : SRS; driven by $\delta n_r E_0$

Plasma Response

δn_b (iaw): driven by $E_0 E_b$

δn_r (epw): driven by $E_0 E_r$

Background plasma:
- described by standard (nonlinear) fluid model
- couples to laser via ponderomotive (radiation) pressure, inverse bremsstrahlung

pF3D models laser propagation on the mesoscale

Z3 simulations couple particle motion to Maxwell's equations in 3D

The National Ignition Campaign

Particle Move:

$$\frac{\mathbf{u}^{n+1/2}-\mathbf{u}^{n-1/2}}{\Delta t}=\frac{q}{m}\left(\mathbf{E}^n+\frac{1}{c}\frac{\mathbf{u}^{n+1/2}+\mathbf{u}^{n-1/2}}{2\gamma^n}\times\mathbf{B}^n\right)$$

$$\mathbf{x}^{n+1}=\mathbf{x}^n+\frac{\mathbf{u}^{n+1/2}\Delta t}{\gamma^{n+1/2}}$$

$$\left(\gamma^{n+1/2}\right)^2=1+\frac{1}{c^2}\left\|\mathbf{u}^{n+1/2}\right\|^2$$

Collect ρ,**J**

Field Solve:

$$\frac{\partial\mathbf{B}}{\partial t}=-c\nabla\times\mathbf{E}$$

$$\frac{\partial\mathbf{E}}{\partial t}=c\nabla\times\mathbf{B}-\mathbf{J}$$

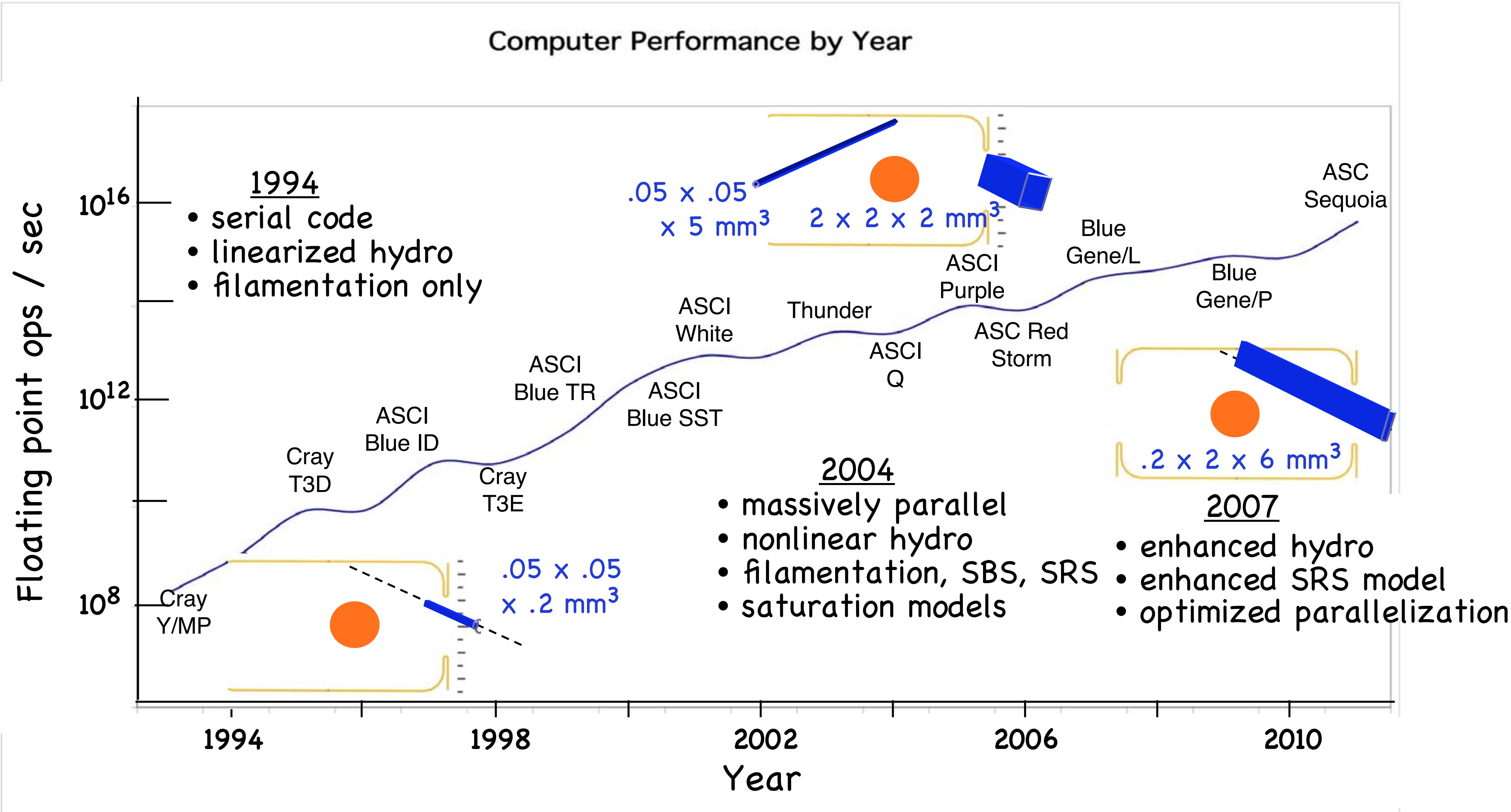
Ensure continuity:

$$\nabla^2\delta\varphi=\nabla\bullet\mathbf{E}-\rho$$

$$\mathbf{E}'=\mathbf{E}-\nabla\delta\varphi$$

Z3 models LPI on the microscale

Rapidly increasing computer performance enables LPI calculations unimaginable twelve years ago



Our grand challenge award enables the unprecedented simulations we perform in support of the National Ignition Campaign

The 2005 Jasons NIF review emphasized the need for 3D LPI simulations of ignition designs

The National Ignition Campaign

- Prior to 2005: one whole beam simulation performed on Thunder under early science runs (300 eV)
  - -- didn't include effects of transverse gradients in the plasma profiles
  - -- ignition design has significantly evolved since the Thunder simulation

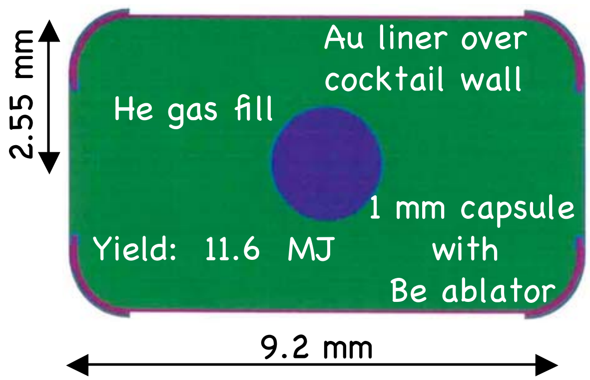
- Fall 2006: first whole beam simulation with transverse gradients on 4096 Purple cpus (300 eV)
  - -- simulation of outer beam propagating through gold blow-off near the wall
  - -- spot size, power, and plasma conditions have further evolved in recent designs

- 2007: whole beam simulations with transverse gradients and a realistic beam on 4096-8192 cpus of Atlas (285 eV and 300 eV)
  - -- 300 eV (two whole beam simulations)
  - -- 285 eV (23^0 and 30^0 beam propagation simulations)

Without such simulations, we do not have a complete energetics story for ignition

First beam propagation simulation:
-- inner beam of the point design

300 eV*
0.937 MJ Laser Energy



radii
Inner Beams: 590 x 824 μm^2
Outer Beams: 343 x 593 μm^2

- this point design optimizes a trade-off between large spots (lower intensity) and ability to re-point beams (smaller spots)
- preliminary analyses of the SRS/SBS kinetic gain indicated inner beams were the prime candidate for further LPI analysis

Our goals were to:

- analyze beam reflectivity and transmission
- provide predictive backscatter images and spectra

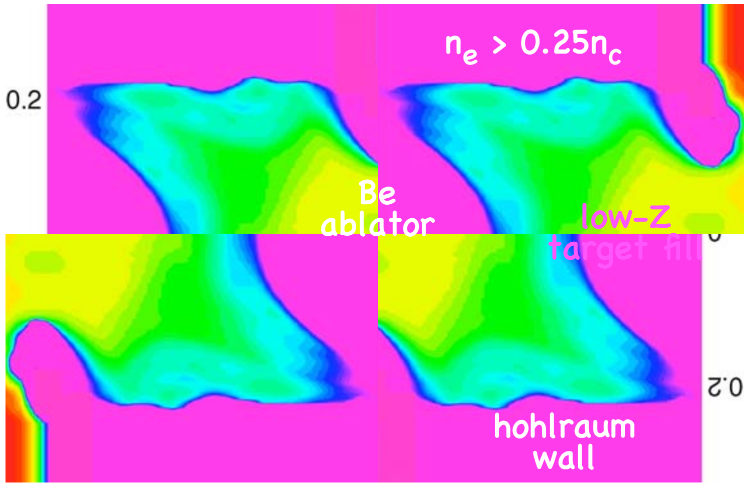
Such simulations had never before been performed

* Design by D. A. Callahan

We were able to simulate beam propagation using nearly all of Atlas

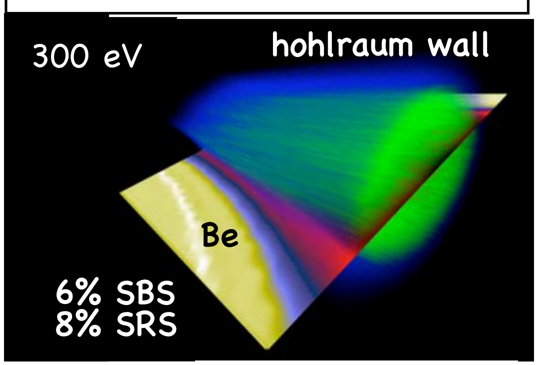
The National Ignition Campaign

Electron Density at Peak Laser Power
300 eV Design

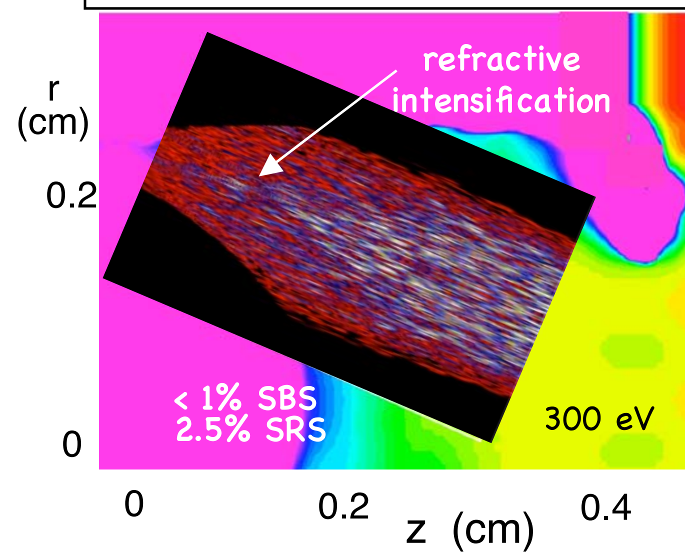


- Near-whole beam (3D) simulations capture effects of transverse gradients and refraction
- capability development performed on rhea and redstorm
- whole beam runs performed on 8192 atlas cpus

First Whole Beam Simulation
For FY09 Ignition Targets:
Propagate Beam 1 mm



Second Simulation:
Propagate Letterbox Beam 3.5 mm
(2D Rendering)



These simulations are unprecedented both in size and in incorporated physics

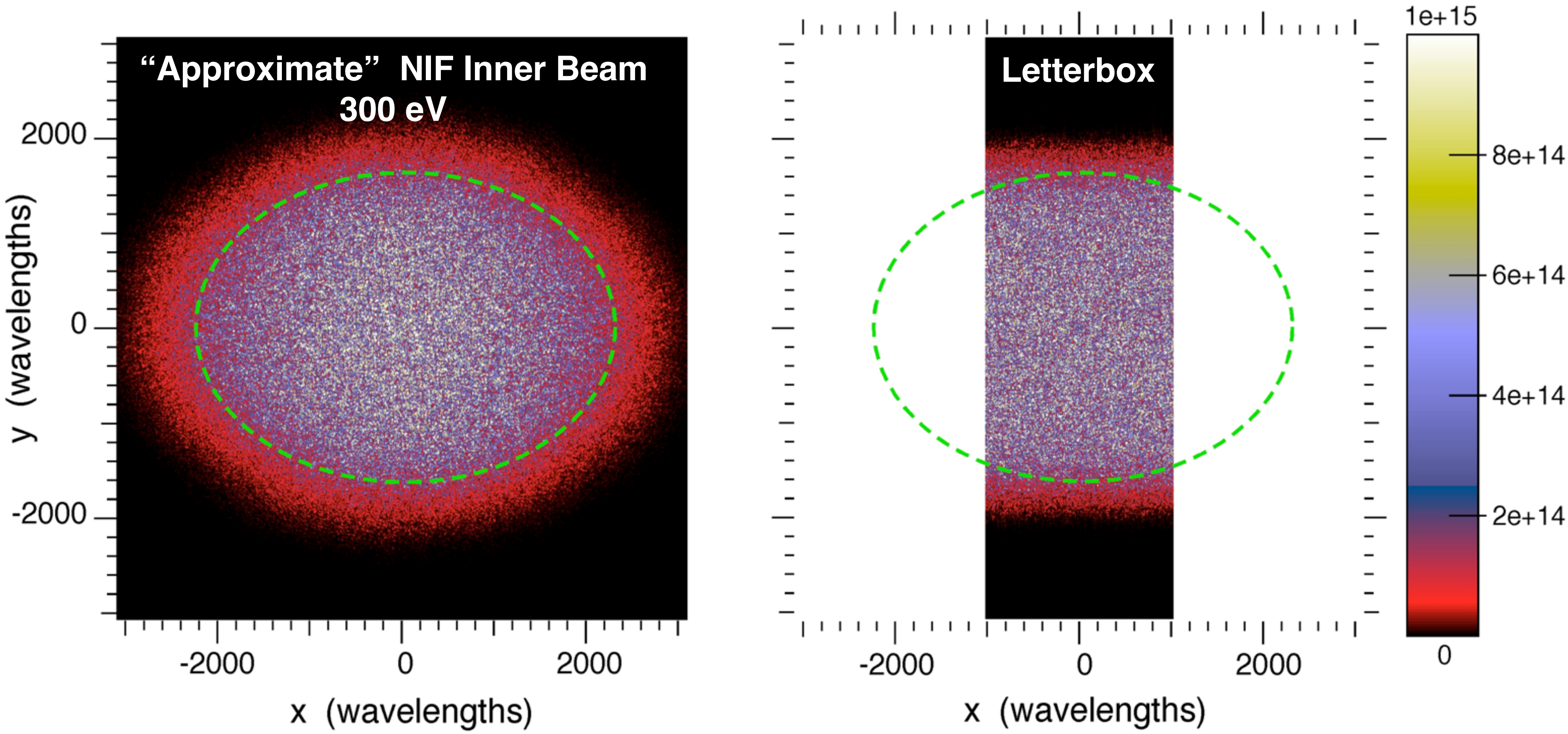
In these massively parallel simulations, we propagate a "letterbox" beam

300 eV: Inner Beam

The National Ignition Campaign

Whole Beam Simulation

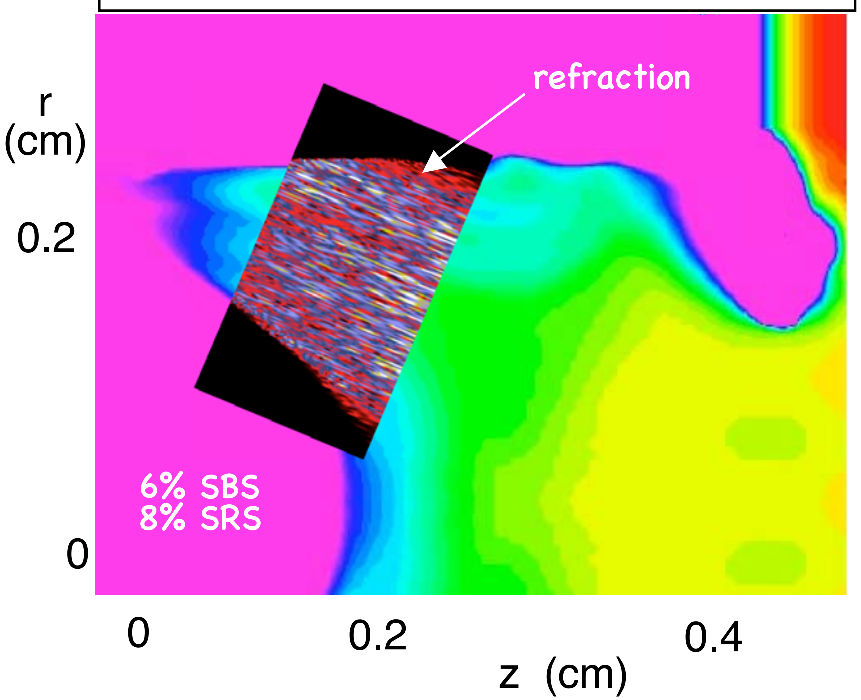
Near-Whole Beam Simulation*



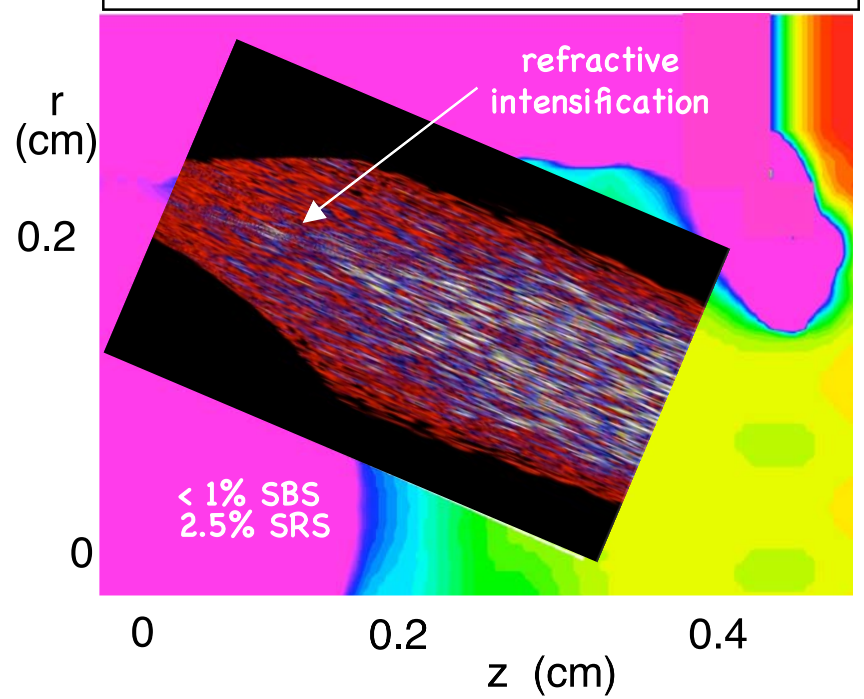
- A letterbox samples all of the radial plasma variations that the full beam does
- This letterbox contains ~ 44% of the total beam power

The whole beam propagated 1 mm, and the letterbox beam propagated 3.5 mm

Propagate Whole Beam
1 mm (2D Rendering)

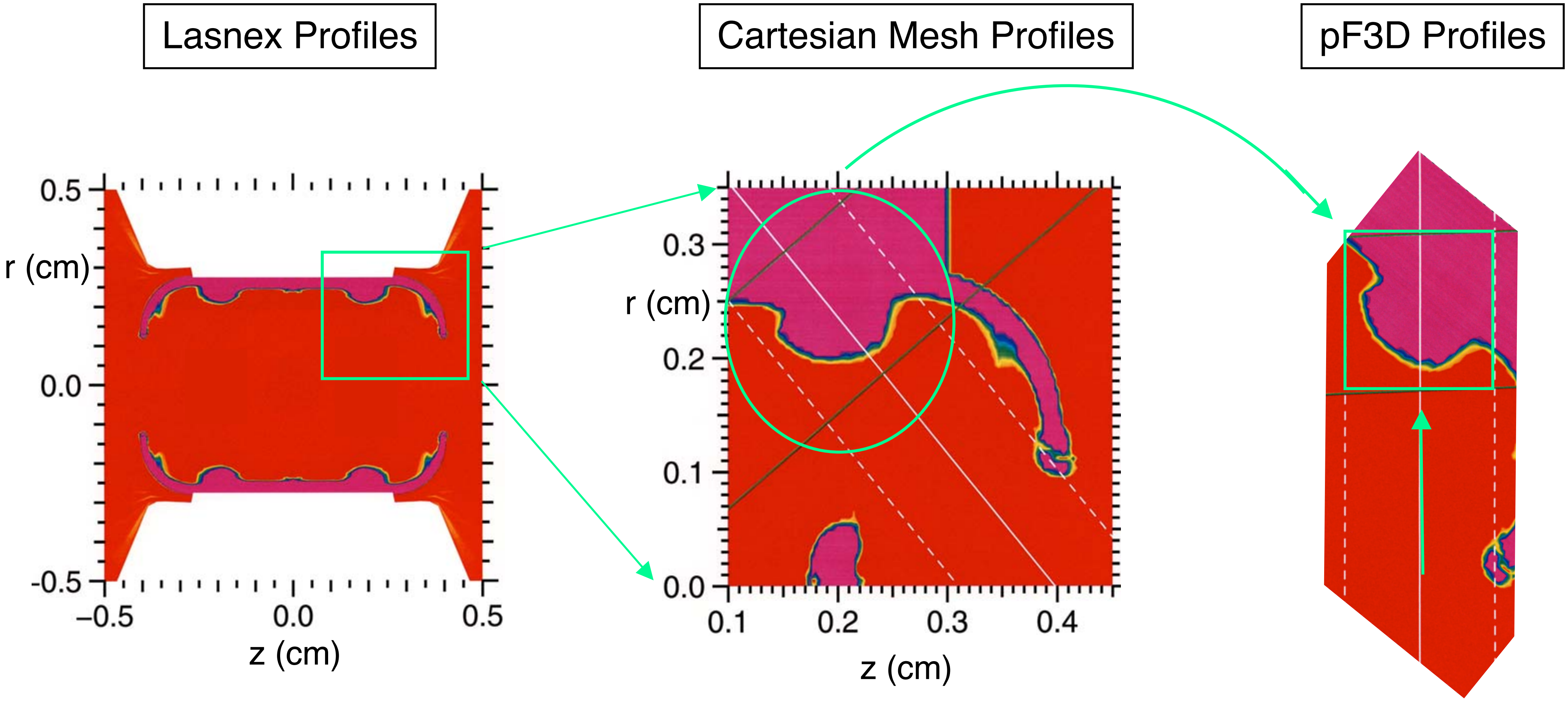


Propagate Letterbox Beam
3.5 mm (2D Rendering)



These simulations capture refractive, scattering and re-absorption effects

We use detailed plasma profiles from rad-hydro simulations near peak power



The two-dimensional Cartesian plasma profiles undergo azimuthal rotation to formulate the 3D pF3D input

Measured reflectivity may be low because backscattered light is re-absorbed

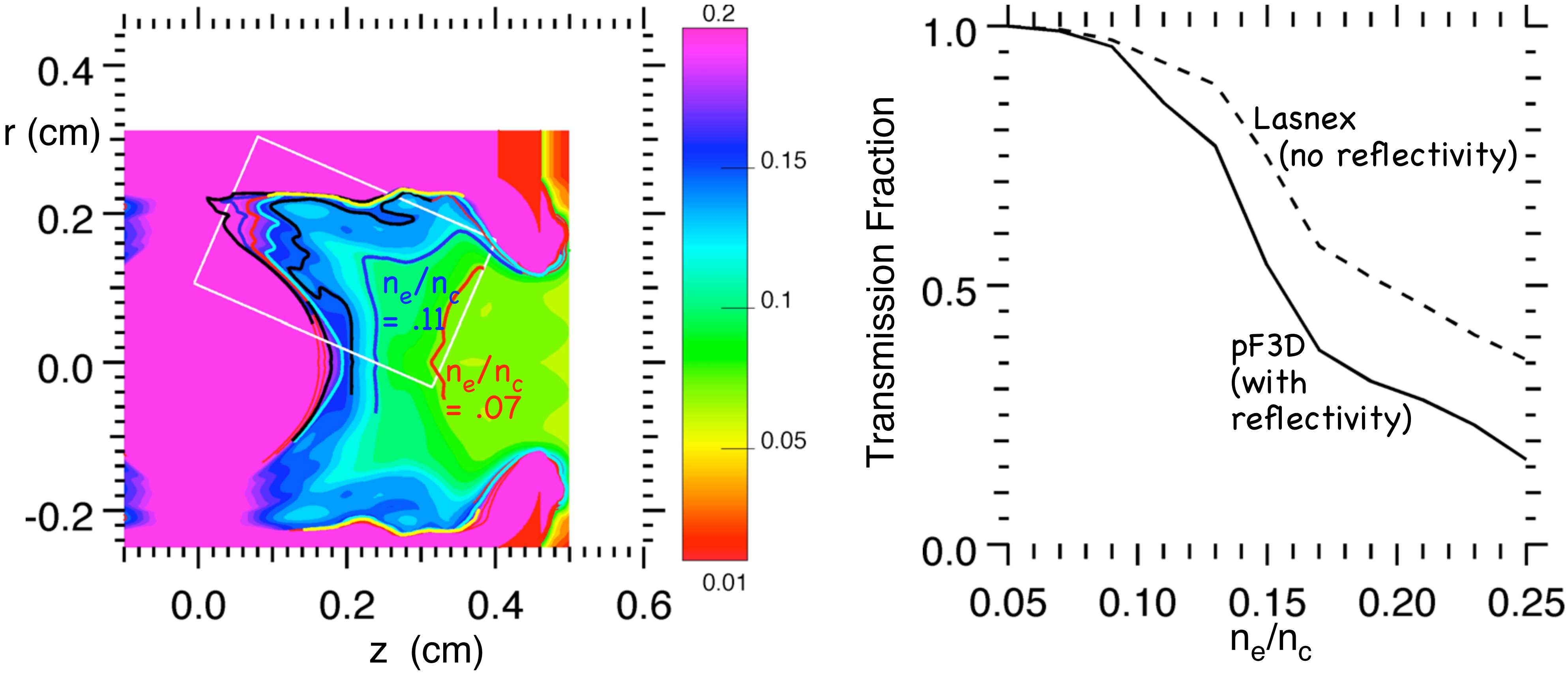
300 eV Inner Beam

The National Ignition Campaign

300 eV Be target -- 23° beam, circa peak power -- R_{total} ~ 3.5%

Calculate transmission through density contours:

Transmission

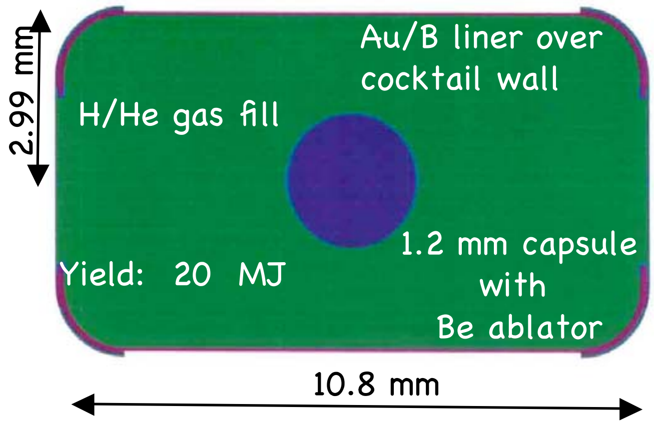


Reduced transmissivity can alter target symmetry;
D. A. Callahan has shown re-tuned symmetry even with impaired propagation

These simulations provided motivation to reduce the radiation temperature from 300 to 285 eV

- at 285 eV, laser intensity is lower ⇨ less reflectivity (linear analysis)

285 eV*
1.21 MJ Laser Energy



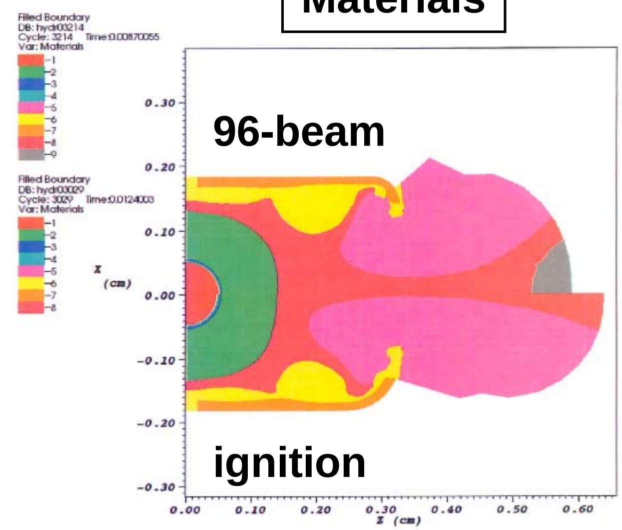
Inner Beams: 693 x 968 μm^2

Outer Beams: 404 x 697 μm^2

96-beam emulator: scale by 60%

285 eV**
0.35 MJ Laser Energy

Materials



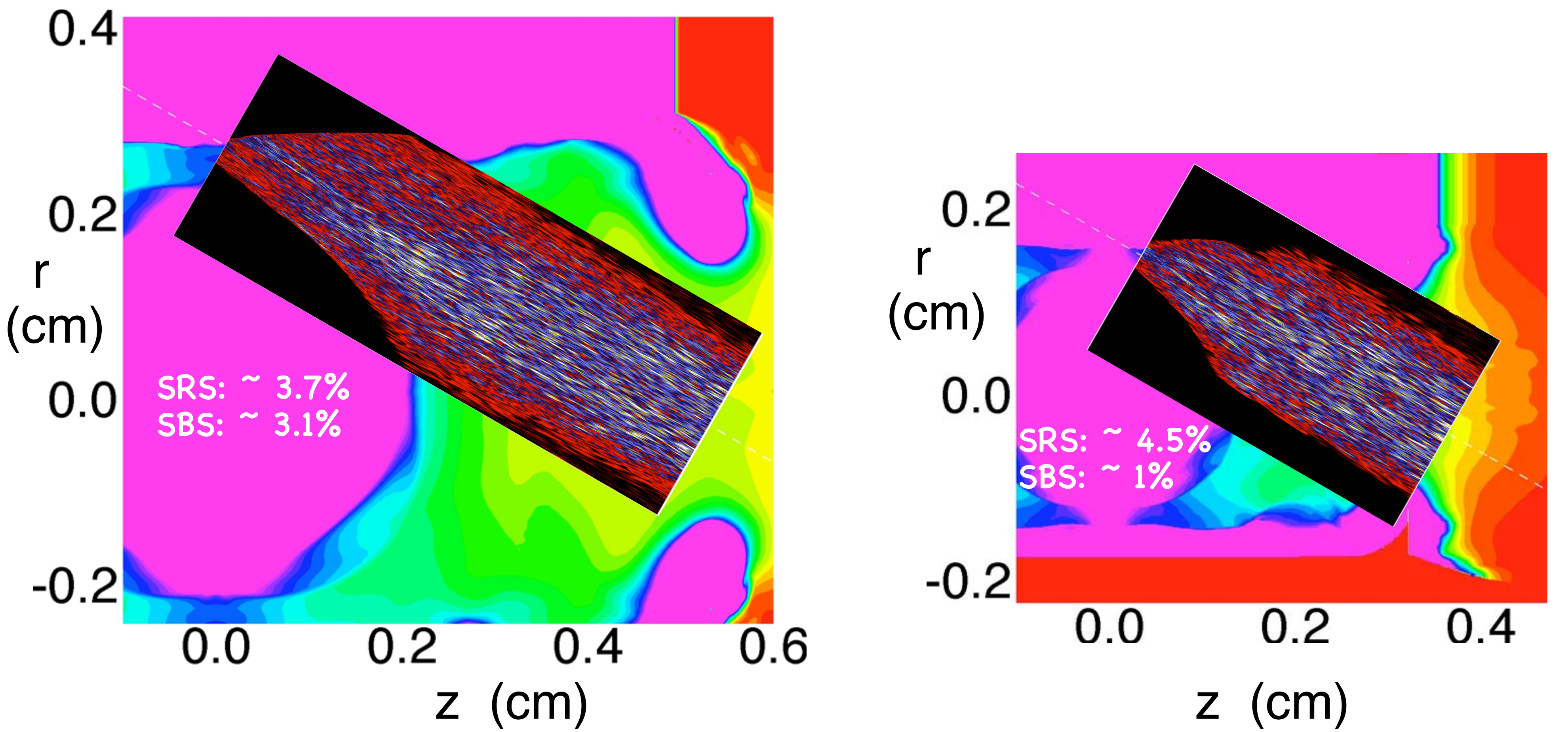
We have also simulated beam propagation in this present point design and its 96-beam emulator

* Design by D. A. Callahan

** Design by N. B. Meezan

Propagation simulations of the 285 eV point design and its emulator show low reflectivity

285 eV Point Design: 30° beam circa peak power	285 eV Emulator: 30° beam circa peak power



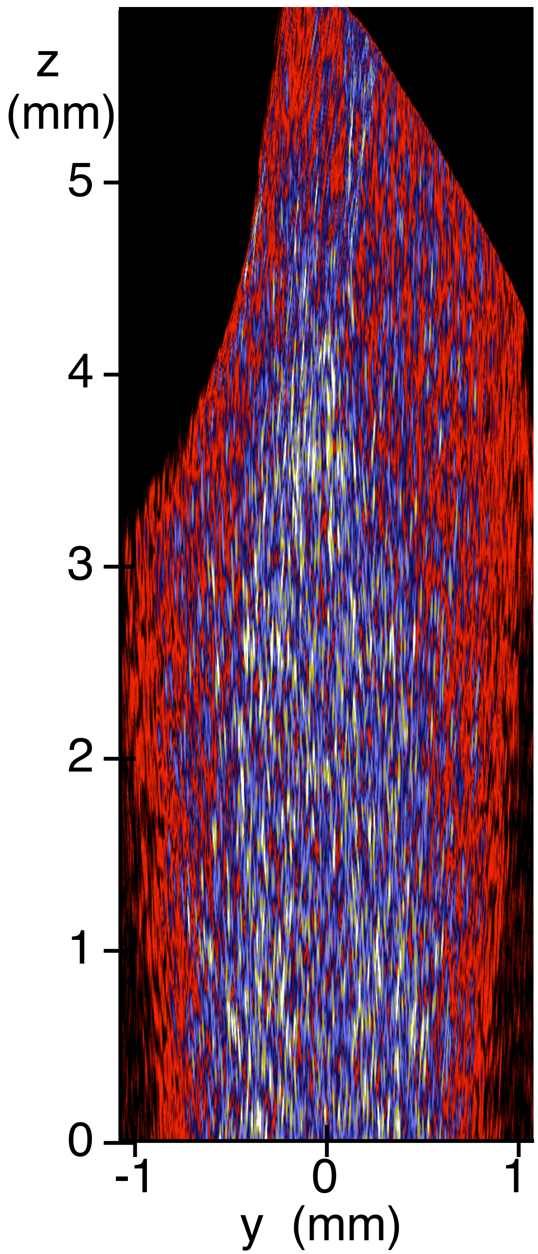
- 4096 Atlas cpus
- ~ 35,000 cpu-days

- 3072 Atlas cpus
- ~ 25,000 cpu-days

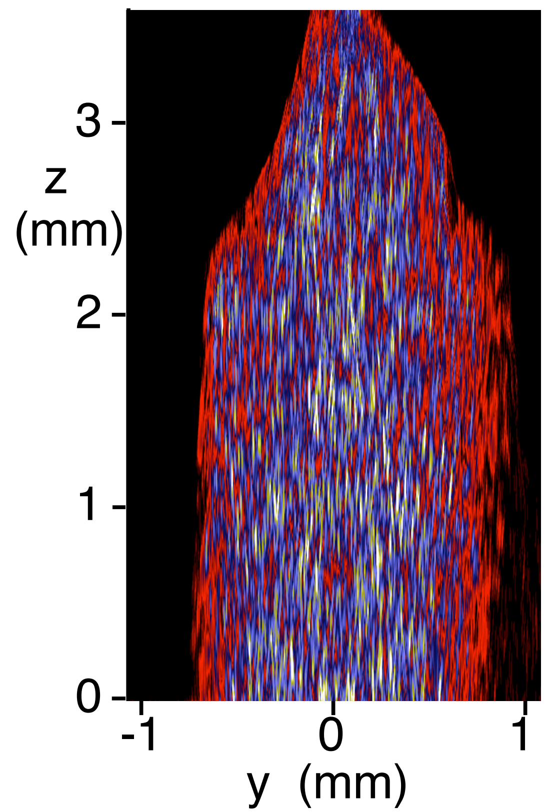
We are currently investigating why reflectivity doesn't scale with the target size

Forward propagating beam for the 285 eV ignition and emulator designs:

285 eV Point Design: 30° beam
circa peak power

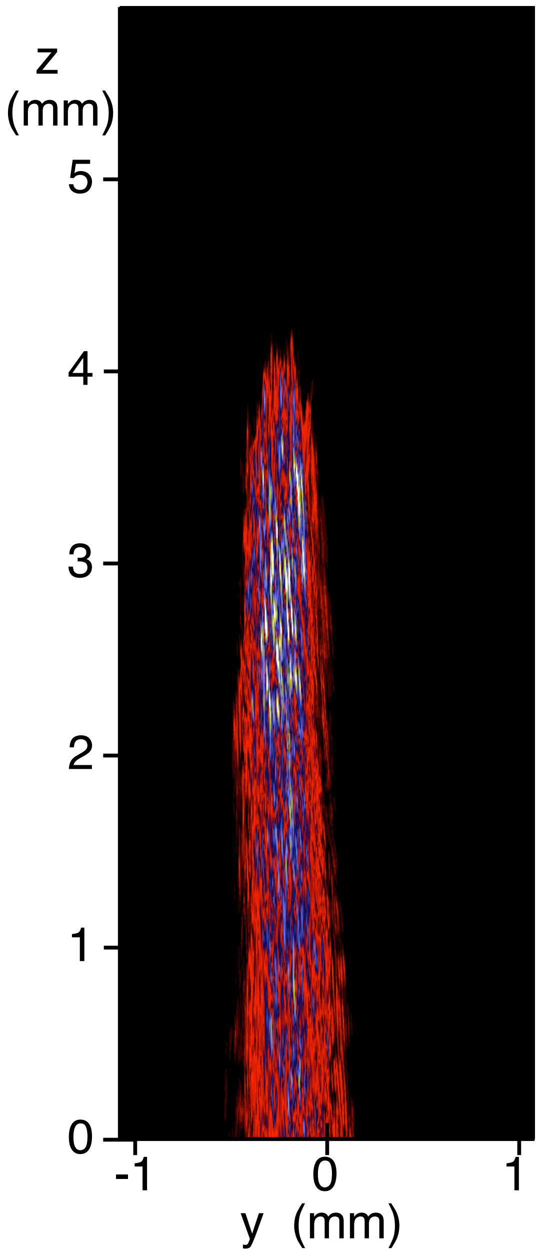


285 eV Emulator: 30° beam
circa peak power

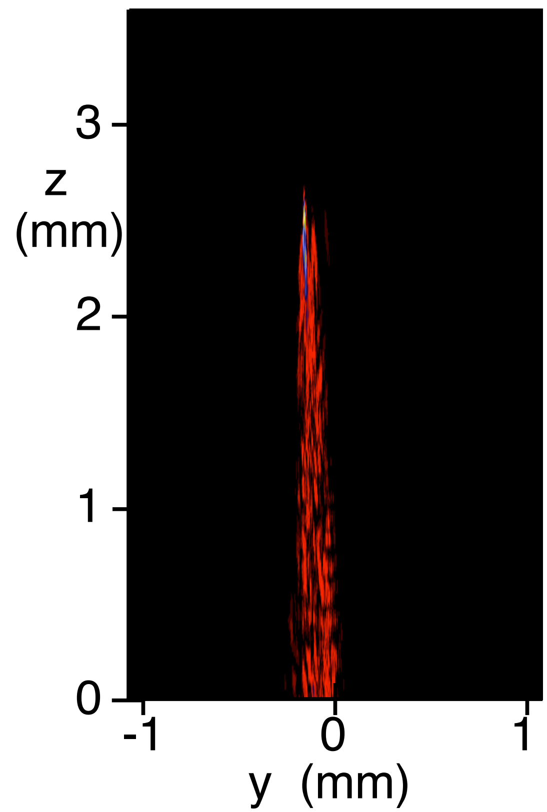


SBS occurs on the capsule side of the beam, in the ablator blow-off

285 eV Point Design: 30º beam
circa peak power



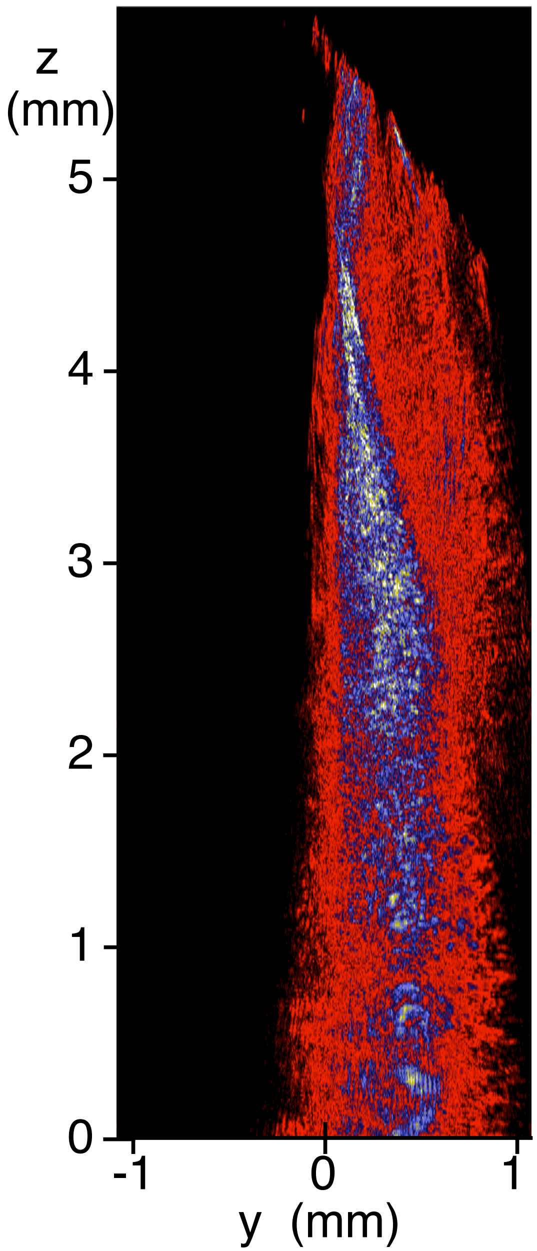
285 eV Emulator: 30º beam
circa peak power



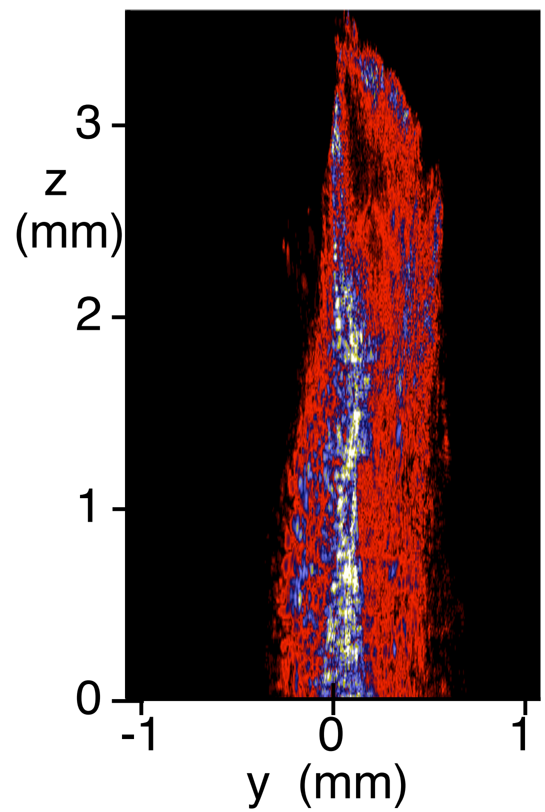
SRS occurs predominantly on the wall side of the beam, in the gas fill

The National Ignition Campaign

285 eV Point Design: 30^o beam
circa peak power



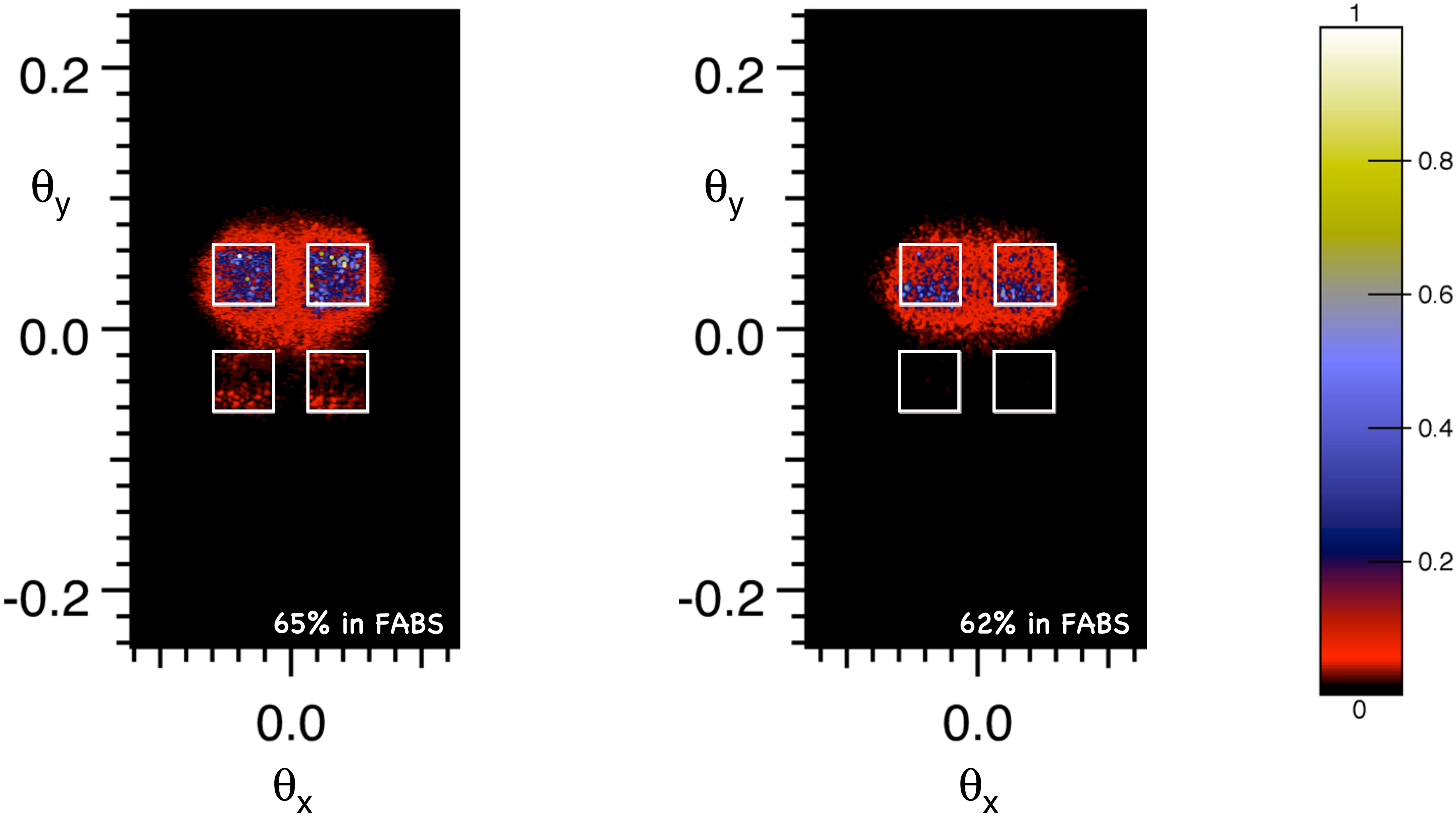
285 eV Emulator: 30^o beam
circa peak power



The majority of the reflected SBS light comes from the upper beams of a quad

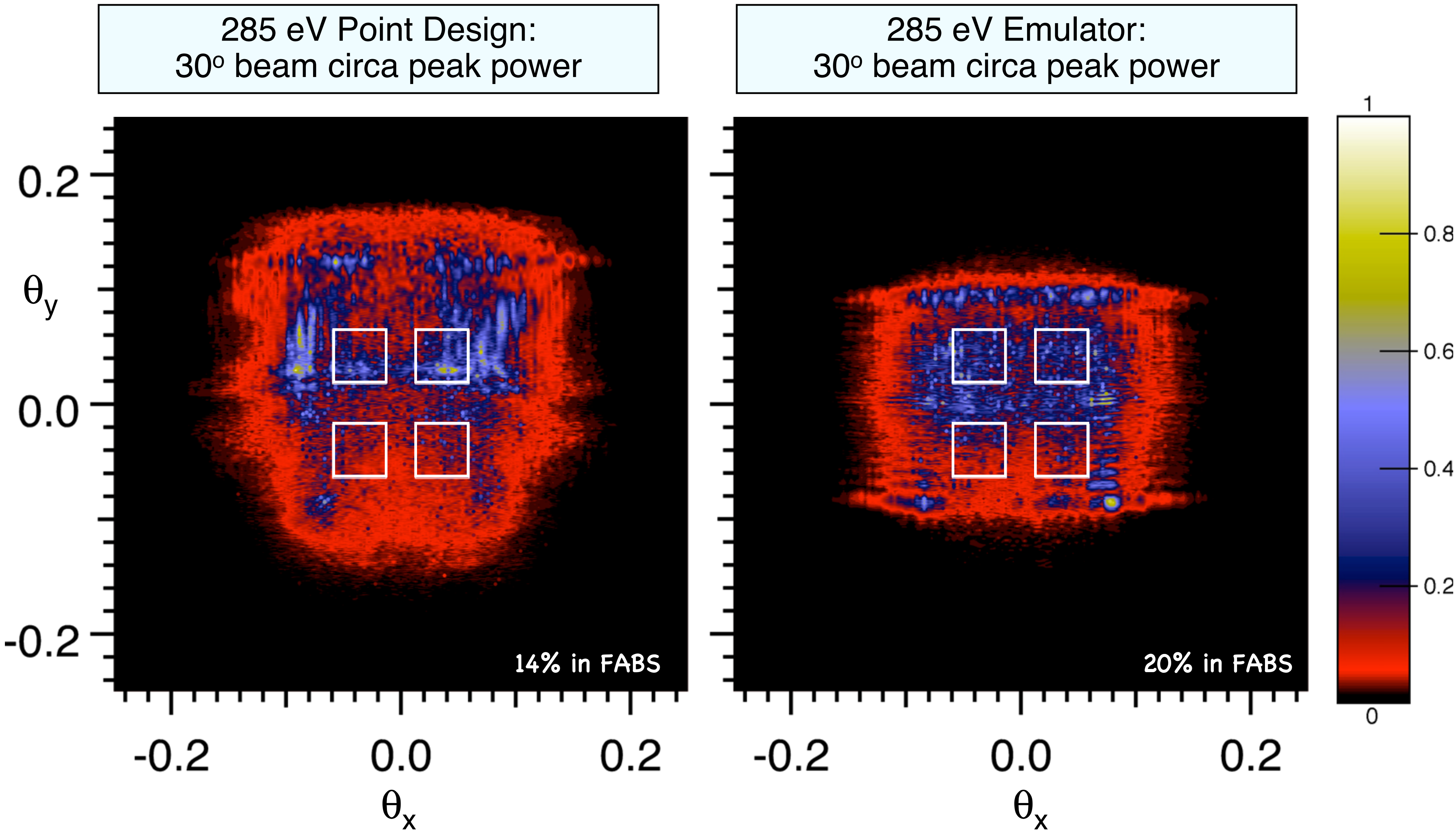
The National Ignition Campaign

285 eV Point Design: 30° beam circa peak power	285 eV Emulator: 30° beam circa peak power



This is consistent with SBS occurring on the capsule side of the beam

The majority of the reflected SRS light is outside the lenses



The longer wavelength SRS light refracts differently than the incident light

3D Z3 simulations show evidence of saturation mechanisms currently not included in pF3D

The National Ignition Campaign

- 3D Z3 simulation at plasma parameters relevant to the 285 eV point design:

  $n_e = 1 \times 10^{21}$ /cm^3, $T_e = 2$ keV,
  $\lambda_0 = 0.351\ \mu$m, $I = 2 \times 10^{15}$ W/cm^2

- simulation volume: 24 x 3 x 130 λ_0^3

- performed on 3072 Atlas cpus for 20,000 cpu-days

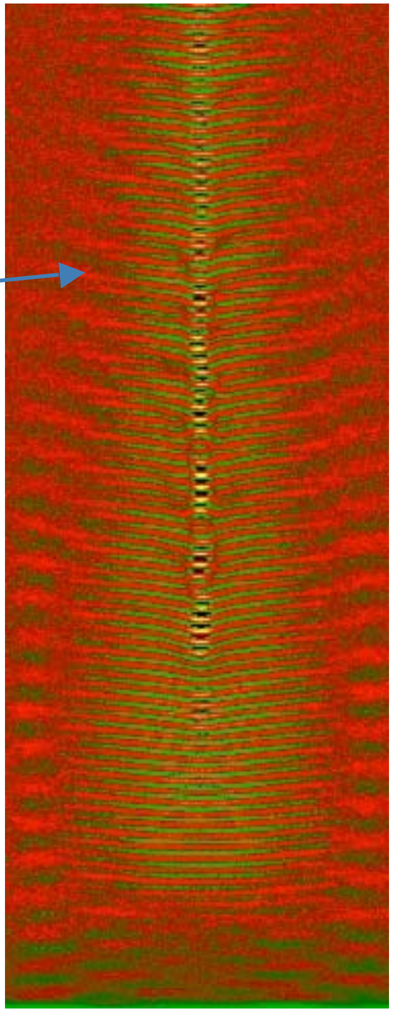
- wavefront bowing: leads to self-focusing and break-up of the wave

  -- can saturate SRS at levels lower than predicted by linear analyses

- phenomenon seen in simulations at lower T_e and higher $I\lambda_0^2$

- first time this has been seen in NIF-relevant plasmas

Electron Plasma Wave Electric Field at y=0



We will be analyzing the energetic significance of this saturation mechanism

In summary, we now have a capability to simulate beam propagation in ignition targets

The National Ignition Campaign

- pF3D scales reasonably well to 8192 Atlas cpus and 32768 bgl cpus
  -- and thus we can perform near-whole-beam simulations

- Z3 scales reasonably well to 8192 Atlas cpus
  -- and thus we can perform near-speckle PIC simulations

- We are able to use macroscale plasma profiles (from Lasnex and Hydra) in pF3D -- includes effects of both axial and transverse gradients

- In the current ignition point design (at 285 eV) we predict low reflectivity (< 7%)
  -- reflectivity may be even lower because of electron plasma wave break-up
  -- transmission is currently under analysis

- Future simulations will be focused on:
  - contingency ignition designs
    -- estimates indicate beam propagation might be better in these targets
    -- such simulations will further guide revising the point design
  - ignition designs using green laser light rather than blue
    -- in these designs, PIC analyses will be critical

The ultimate question: can we scale up to 1 million cpus?